Parameter Analysis and Design of A 1.5GHz, 15mw Low Noise Amplifier

Dan Zhang¹, Wei Wu²
College of Sciences, Shanghai University

Abstract. In this paper, we analyze parameters like noise figure, input impedance match, gain, and linearity of the low noise amplifier (LNA) and design a 1.5GHz, 15mw LNA with inductive source degeneration.

Keywords: low noise amplifier, LNA design

1. Introduction

The increasing demand for portable wireless equipments, such as cell phones, GPS, Bluetooth (2.4GHz) has spurred great improvement in low-power RF circuits with high reliability. The low noise amplifier (LNA), which is the first block in the RF receiver front end (shown in Fig.1), plays a significant role in amplifying weak signals reaching the antenna while at the same time reduces noise and maintains a low power consumption. Thus, when designing a LNA that meets specific performance requirements, one should take into consideration the gain, power, noise figure, input and output impedance match (the S-parameter), and linearity of the LNA.

The inductive source degenerated cascode LNA topology, shown in Fig.2, has demonstrated the potential for excellent impedance matching, noise figure, and power dissipation [1] when compared to LNA that has resistive termination, 1/g_m termination, or shunt-series feedback of the input port.

In section 2, we study several basic parameters of the LNA with inductive source degeneration; in section 3, we offer an example of the design of a LNA; in section 4, we use ADS and PSPICE to analyze the performance of the designed LNA.

2. Parameter analysis

The following passage will study the noise figure, input impedance match, gain, and linearity of the inductive source degenerated cascode LNA.

2.1. Noise figure (NF)
The noise figure is the ratio between the total output noise power due to all noise sources and the output noise power generated by the source internal resistance [2]. The LNA should not bring too much noise to the following part of the receiver in order to select and amplify the weak signals, so keeping a low NF is a crucial process when designing the LNA. According to the n-stage network Friis equation:

\[
NF_{\text{tot}} = 1 + \frac{(NF_1 - 1)}{A_{p1}} + \ldots + \frac{(NF_n - 1)}{A_{p1 \ldots A_{p(n-1)}}},
\]

where \( A_p \) is the gain of the stage and is usually high, we can discard the noise contribution of the later stages on overall noise figure calculation [3], which means we could only focus on the noise situation of M1, which is shown in Fig.3.

\[
NF_{\text{tot}} = 1 + \frac{(NF_1 - 1)}{A_{p1}} + \ldots + \frac{(NF_n - 1)}{A_{p1 \ldots A_{p(n-1)}}},
\]

where \( A_p \) is the gain of the stage and is usually high, we can discard the noise contribution of the later stages on overall noise figure calculation [3], which means we could only focus on the noise situation of M1, which is shown in Fig.3.

Fig.3. Equivalent small signal circuit of M1 Fig.4. More hardware in the input matching network

It contains current noise in drain (\( i_{\text{drain}} \)), current noise in gate (\( i_{\text{gate}} = i_{\text{drain}} + i_{\text{gate}} \)), resistance noise from \( R_g \) and \( L_g \) (\( i_{\text{drain}} \) and \( i_{\text{gate}} \)). The noise figure of such LNA can be expressed as:

\[
F = 1 + \frac{R_{Lg} + R_e}{R_e} + \frac{2\chi Q_0}{\alpha Q_k} \left( \frac{\alpha_b}{\alpha} \right)^2 (1),
\]

\[
\delta = \kappa + \xi = 1 + 2\left| Q_0 \right| \sqrt{\frac{\delta \xi^2}{5\gamma}} + \frac{\delta \chi^2}{5\gamma} (1 + Q_0^2) (2). \]

\( \delta \) is the gate noise, \( \gamma \) is the thermal noise in the channel of M1, \( \alpha = \frac{g_{m1}}{g_{d01}} \) (\( \alpha = 1 \) in long-channel devices), \( Q_0 \) is the quality factor of input match network and equals \( \frac{1}{\omega_b R_e C_{gr1}} \), \( C_{gr1} = \frac{2}{3} W/L C_m \), \( \kappa = 0.395 \) (even consider the short-channel effect [4]), \( \omega_b \) is the work frequency and \( \omega_r = \frac{g_{m1}}{C_{gr1}} \) is the resonance frequency.

From (1) and (2), we can easily realize that when \( Q_{L,\text{opt}} = \sqrt{1 + \frac{5\gamma}{\delta \xi^2}} \) (\( Q_{L,\text{opt}} \) is usually between 3.5 and 5.5, if the channel resistance is considered, then \( Q_{L,\text{opt}} = \sqrt{1 + \frac{5\gamma}{\delta \xi^2} + 2\left| Q_0 \right| \sqrt{\frac{\delta \xi^2}{5\gamma}} (1 + Q_0^2) [5]) \). F reaches its minimum that equals:

\[
W_{\text{opt}} = \frac{3}{2L C_m \omega_b R_e Q_{L,\text{opt}}^2} (3)
\]

2.2. Input impedance match

In Fig.3, the input impedance of the LNA can be expressed as:

\[
Z_m = sL_g + R_{Lg} + R_e + Z_l, \quad \text{where} \quad Z_l = sL_e + \frac{1}{sC_{gr1}} + \alpha_b L_e.
\]

Therefore, we can adjust \( L_e \) to make the input impedance that equals \( R_e \) (50 Ω) when working frequency is near \( \omega_b \), which means \( Z_m = \text{Re}(Z_m) = \omega_b L_e \rightarrow R_e \) (neglect \( R_{Lg} \) and \( R_e \) [6]). Thus, \( L_e \) and \( L_g \) can be designed as follows:

\[
L_e = \frac{R_e}{\omega_b}, \quad L_g = \frac{1}{\omega_b C_{gr1}} - L_e.
\]
Sometimes we can add additional hardware to the input impedance matching network to provide more degrees of freedom in the design, in order to mitigate the impact of component variations for LNA [7], shown in Fig 4, while this structure accounts for more area on the chip.

### 2.3. Gain

The small signal analysis for cascode is shown in Fig.5.

![Fig.5. Small signal equivalent circuits for cascode LNA with inductive source degeneration](image)

From this equivalent circuit, we can acknowledge that the transconductance \( G_{mi} \) of the first stage (common-source) can be expressed as:

\[
G_{mi} = \frac{g_{mi}}{sC_m(sL_n + sL_g + R_s) + 1 + g_m sL_n},
\]

and the current gain \( A_2 \) of the second stage (common-gate) can be expressed as:

\[
A_2 = \frac{g_{m2}}{g_{m2} + sC_m^2}.
\]

Consider that \( g_m = \mu C_m W/L(V_{gs} - V_{tn}) \), for a certain technology like 0.18 \( \mu m \) or 0.25 \( \mu m \), all parameters are fixed except the channel width. So we can increase \( W \) to achieve greater gain for the weak signals. According to (3), however, expanding width could elevate noise figure and introduce more noise to the LNA. What is more, bigger \( g_m \) means greater drain current \( I_D \), which rise the total power consumption that equals \( V_{DD} \times I_D \).

### 2.4. Linearity

Although there are many ways to evaluate the linearity of the LNA, to measure the third-order intercept point (IP3) is the most commonly used method. The IIP3 is obtained graphically by plotting the output power versus the input power both on logarithmic scales. Two curves are drawn: one for the linearly amplified signal at an input tone frequency, one for a nonlinear product. Both curves are extended with straight lines of slope 1 and 3. The point where the curves intersect is the third-order intercept point, which is shown in Fig.6.

![Fig.6. Third-order intercept point definition](image)

For narrow-band LNA, the IIP3 can be expressed as:

\[
\text{IIP3} = \frac{4V_{sat}^2}{g_m Q_s \sqrt{R_s}} \left| g(0) \right| + g(v) + g(-v) - 2g(0),
\]

where \( g(0) \), \( g(v) \), \( g(-v) \) are transconductances got when the input signal voltage is 0, \( v \), \( -v \), respectively. To obtain a higher IIP3, one can increase the overdrive voltage while at the same time rise the power dissipation, or lower the quality factor of the input circuit while worsen the noise figure of the LNA. Thus, there exist necessity to best optimize the parameters of the LNA during designing process.

### 3. Design of a 1.5GHz, 15mw LNA with inductive source degeneration

To design a LNA that meets the specific performance requirements shown in Table 1, one should first figure out values of the important components of the LNA as follows:

\[
I_d = \frac{P}{V_{DD}} = 10mA; \quad L_s = R_s / \omega_s = R_s C_g / g_m = 4R_s L / (3\mu_s E_{sw}) = 0.6nH; \quad L_n = 1/(\omega_n^2 C_m) - L_s = 42.2nH;
\]
\[ W_{opt} = \frac{3}{2LC_{ox} \omega_0 R_{ox} Q_L} = 500 \mu m \] (4)

Then we can design a whole LNA structure with specific components values in Fig.7. The widths of M1, M2, M3, M4 are 500 \( \mu m \), 200 \( \mu m \), 50 \( \mu m \), 50 \( \mu m \), respectively.

<table>
<thead>
<tr>
<th>channel length ((L))</th>
<th>0.35 ( \mu m )</th>
<th>( \mu_m )</th>
<th>0.05 ( m^2/V\cdot s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>supply voltage ((V_{DD}))</td>
<td>1.5V</td>
<td>( E_{sat} )</td>
<td>4( \times )10^8 ( V/m )</td>
</tr>
<tr>
<td>power ((P))</td>
<td>15mw</td>
<td>( R_s )</td>
<td>50 ( \Omega )</td>
</tr>
<tr>
<td>working frequency ((\omega_0))</td>
<td>1.5GHz</td>
<td>( R_s )</td>
<td>200 ( \Omega )</td>
</tr>
<tr>
<td>( C_{ox} )</td>
<td>3.8mF/ ( m^2 )</td>
<td>( Q_L )</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. specific requirements for designing

4. Simulation results

4.1. S-parameters, NF, Stability factor and IIP3

We use the Advanced Design System 2006A (ADS) to optimize the value of inductors and capacitors, in order to achieve input and output impedance match, to obtain a relatively higher gain together with a smaller noise figure, and to keep stability factor greater than one. We finally set \( L_1 \) to 0.36 \( nH \) and \( L_2 \) to 38.5 \( nH \). The simulation results of S-parameters, stability factor, noise figure, and the third-order intercept point are shown in Fig.8. When working at the frequency of 1.5GHz, the LNA has the following property: S11, S22, S21, NF, and IIP3 are -11.335dB, -12.490dB, 12.149dB, 2.050dB, and 5.2dBm, respectively. The stability factor is 1.321, being greater than 1, which indicates the LNA is stable near 1.5GHz.

Fig.8. Simulation results

Fig.9. Output signal versus width

\((\triangle 600 \mu m \bigtriangleup 500 \mu m \bigtriangleup 400 \mu m)\)
4.2. The relation between gain and channel width

We use PSPICE LEVEL 3 model which is suitable for short-channel MOSFET to simulate the output of the designed LNA in order to study its gain. The program codes for the structure in Fig.7 are provided as follows:

```
A LNA CIRCUIT
*PARAM WIDTH=500U
Udd 1 0 1.5V
Vin 8 0 AC 1
*Vin 8 0 SIN(0 0.1 1.5G)
C3 1 2 10fF
R1 1 2 2.6K
L1 1 3 4nH
C4 3 0 1pF
R2 4 6 7K
C1 8 7 10p
Lg 7 6 42.2nH
Ls 9 0 0.6nH
M1 5 6 9 0 NM L=0.35U W={WIDTH}
M2 3 2 5 0 NM L=0.35U W=200U
M3 2 4 0 NM L=0.35U W=50U
M4 4 0 0 PM L=0.35U W=50U
.PROBE
.END
```

Since $g_{m1}$ increases when the channel width of M1 is greater, the weak signals can be amplified further if we set a wider channel. It is proved by the simulation results shown in Fig.9.

Consider the fact that LNA lays more emphasis on lowering noise figure than increasing gain, we should sacrifice high gain in order to reduce the output noise. Usually, the gain achieved with the minimum noise figure is 2 to 4dB less than the maximum value [8].

5. Conclusions

The low noise amplifier (LNA) is a crucial part in RF receiver. It is designed for selecting and amplifying weak signals in certain frequency, reducing noise, and providing an appropriate working condition for the following mixer. We first analyze some parameters, such as noise figure, input impedance match, gain, and linearity, that reflect the quality of LNA. Then we designed an inductive source degenerated cascode LNA with the working frequency of 1.5GHz. The simulation results got from ADS and PSPICE indicate that the values of the components are appropriate and the performance of the designed LNA is acceptable.

6. References


